

The Abundance of Oxygen in the Sun

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The forbidden O I lines at $\lambda\lambda 5577$, 6300, and 6363 appear as faint absorption lines in the solar spectrum. Measurements of the equivalent widths indicate that the reversing layer has 7×10^{20} oxygen atoms per square centimeter. Comparison with the equivalent widths of the infra-red permitted lines yields an excitation temperature of 5200° for oxygen. The possibility of using forbidden lines for determining the abundance of other light elements is discussed.

IN previous studies of the chemical composition of the sun the abundance of oxygen has been based on the intensities of the two infra-red multiplets at $\lambda 7773$ and $\lambda 8446$, which have the very high excitation potentials of 9.11 and 9.48 volts, respectively. The Boltzman factor which determines the ratio of the number of atoms in the ground state to the number in the lower state of the observed multiplets is, therefore, very large, being of the order of 10^9 . Furthermore, the excitation temperature that must be used in the Boltzman factor for these high excitation-potential states differs by a substantial but unknown amount from the temperature obtained from the relative intensities of the metallic lines of lower excitation potential. This uncertainty in the temperature, combined with the very large value of the Boltzman factor, leaves the number of oxygen atoms present in the reversing layer, as calculated by this process, in doubt by a very substantial factor.

The only low excitation-potential lines of the oxygen atom in the astronomically observable range are the forbidden lines at $\lambda\lambda 5577$, 6300, and 6363. The *Revised Rowland* lists a line of intensity -2 at wave-length 5577.344 in satisfactory agreement with the wave-length of the green auroral line determined by Babcock¹ with an interferometer at 5577.350A and with the laboratory wave-length of this line determined by Cario² at 5577.348A, and by McLennan and McLeod³ at 5577.341A. In terrestrial sources the two other forbidden lines are very much fainter than $\lambda 5577$. For this reason, the best deter-

mination of their wave-lengths that has been made was with a prism spectrograph having a dispersion of only 29A/mm. This determination unfortunately is not accurate enough to permit a positive identification of these lines in the solar spectrum. A redetermination of the wave-lengths of these lines was, therefore, made from spectrograms of HD 45677 taken with the coude grating-spectrograph of the 100-inch telescope with a dispersion of 20A/mm. In HD 45677 these two forbidden lines appear as relatively strong, sharp emission lines. The radial-velocity correction was obtained from measures of the [Fe II] lines which are also well developed in emission in this object. The new determination of these wave-lengths removes most of the discrepancy that had formerly existed between the wave number separation of the $2p^4\ ^3P_2$ and $2p^4\ ^3P_1$ terms determined from these red forbidden lines and from the extreme ultraviolet permitted transitions to these levels.

The first and second columns of Table I summarize the evidence from the wave-length standpoint for the presence of the forbidden O I lines in the solar absorption spectrum and list the principal permitted lines that are also present. In the first column, the wave-lengths are taken from the *Revised Multiplet Table*, except for the lines at $\lambda 6300$ and $\lambda 6363$, whose wave-lengths were obtained from HD 45677, discussed above. Except for the wave-length of the line at 6363A, all wave-lengths in the second column are taken from the *Revised Rowland*. While the $\lambda 6363$ line does not appear in the *Revised Rowland*, recent high dispersion, high contrast plates of this region all definitely show a line at the wave-length listed in this column.

The three forbidden lines were photographed

¹ H. D. Babcock, Mt. W. Contribution No. 259; Ap. J. 57, 209 (1923).

² G. Cario, Zeits. f. Physik 42, 15 (1927).

³ McLennan and McLeod, Proc. Roy. Soc. A115, 515 (1927).

TABLE I. The number of oxygen atoms in the reversing layer.

λ RMT or HD 45677	λ Sun	Transition	Transition probability A (sec. ⁻¹)	f	Excitation potential	Observed equivalent width W	Number of atoms in lower state	Total oxygen atoms per sq.cm.
5577.350	.344	$2p^4\ ^1D - 2p^4\ ^1S$	2.2	...	1.96	0.0036A	6×10^{18}	9×10^{20}
6300.32	.331	$2p^4\ ^3P_2 - 2p^4\ ^1D$	0.0078	...	0.00	0.0047	3×10^{20}	5×10^{20}
6363.75	.80	$2p^4\ ^3P_1 - 2p^4\ ^1D$	0.0026	...	0.02	0.0018	2×10^{20}	6×10^{20}
7771.96	.954	$3s^5S - 3p^5P_3$	.....	0.35	9.11	0.071	4×10^{11}	5×10^{20}
7774.18	.177	$3s^5S - 3p^5P_2$	.....	0.25	9.11	0.065	5×10^{11}	6×10^{20}
7775.40	.395	$3s^5S - 3p^5P_1$	.....	0.15	9.11	0.049	6×10^{11}	7×10^{20}
8446.35	.359	$3s^3S - 3p^3P_{0,2}$	.....	1.0	9.48	0.124	2×10^{11}	9×10^{20}
8446.76	.741	$3s^3S - 3p^3P_1$						
Mean								7×10^{20}

in light from the center of the solar disk, with dispersions of 0.34 and 0.7A/mm on IV F or Solar Green A plates developed to a gamma of 4 to 7. The equivalent widths, W , of the forbidden lines listed in the seventh column of Table I were obtained from the average of measurements of six to eleven microphotometer curves for each line. The equivalent widths of the permitted infra-red lines given in the same column were determined from measurements of the microphotometer curves in the *Utrecht Photometric Atlas of the Solar Spectrum*.

All these lines are well separated from strong lines. The line at $\lambda 5577$ has adjacent faint lines on both sides that make the location of the height of the continuous background somewhat doubtful. None of these lines are attributed to other elements in the *Revised Rowland*, although the *Revised Multiplet Table* lists a Ni I line of intensity 1 at $\lambda 6300.363$. This line does not appear in the *M.I.T. Wave Length Tables*, and, in fact, has been observed in only two investigations of the Ni spectrum. In one of these investigations it was found on only one plate. Some slight question exists, therefore, as to the reality of the line. In any case, the relative intensities, in the solar spectrum, of other Ni lines that arise from the same lower level as $\lambda 6300.363$ indicate that Ni is probably not the major contributor to the solar line at $\lambda 6300.331$.

Some light is thrown on the reality of the identification of all these forbidden lines and of the $\lambda 6300$ line, in particular, by the width of the lines at half-depth. For comparison, the widths at half-depth of nine Ni I lines were measured on the microphotometer curves of the *Utrecht*

Photometric Atlas of the Solar Spectrum. These nine lines included all those between $\lambda 5800$ and $\lambda 6600$ which have the same lower term ($y\ ^3D$) as the $\lambda 6300.363$ line and which are well separated from other lines and have depths between 0.10 and 0.25 of the continuous background. The mean value of the width at half-depth divided by the wave-length for those Ni lines is 1.75×10^{-5} , with a maximum deviation from the mean of 0.08×10^{-5} . The average of the same quantity for four permitted oxygen lines, including those of the $\lambda 7773$ multiplet and the line at $\lambda 6158.19$, is 2.8×10^{-5} . Measurements of the microphotometer curves obtained in the course of the present investigation give the following values for the solar lines identified as [O I]: $\lambda 5577$, 3.4×10^{-5} ; $\lambda 6300$, 2.2×10^{-5} ; $\lambda 6363$, 2.7×10^{-5} . These measurements would seem to indicate that the solar lines at $\lambda 5577$ and $\lambda 6363$ have their origin in an atom of about the atomic weight of oxygen. The line at $\lambda 6300$, while definitely wider than the Ni lines, is also narrower than would be expected for an oxygen line. Furthermore, its microphotometer curves have a V-shape rather than the U-shape of the other two forbidden lines. All these observations suggest strongly that the $\lambda 6300$ line is made up of a broad oxygen line on which is superimposed a nearly coincident narrow Ni line. The narrow Ni component is then responsible for the observed V-shaped tip at the bottom of the line and for a substantial increase in the depth of the line. On the other hand, it probably does not contribute more than 10 to 30 percent of the total equivalent width of the line. Because of the small and uncertain contribution of Ni to the equivalent width of the line, no cor-

rection for the possible presence of this component has been made in the abundance determined from the equivalent width.

The forbidden lines were photographed also with light from both the east and west limbs of the sun; all show the standard displacement of solar lines in such a way as to leave no doubt that they are of solar rather than of telluric origin. The equivalent widths of the forbidden lines are roughly one-fourth greater at the limb than at the center of the disk.

The number of atoms per square centimeter of the reversing layer in the lower state of each transition is listed in the eighth column of Table I. These numbers were calculated from the equivalent width with the aid of formula (1),

$$N = \frac{Wmc^2}{f\pi e^2\lambda^2} = \frac{(2J'+1)}{(2J+1)} \frac{8\pi cW}{A\lambda^4}, \quad (1)$$

in which J' and J are the J values of the lower and upper states, respectively. This formula is valid only for the linear portion of the curve of growth. Since the maximum depth of the strongest line under consideration is only 0.27 of the continuous background, it is evident that this formula is applicable with sufficient accuracy to all the lines.

For the forbidden lines the transition probabilities, A , in the fourth column in Table I were taken from Pasternack.⁴ No values for the transition probabilities of the permitted lines in the infra-red are available; consequently, estimates were made of the f -values of these lines with the aid of the Thomas-Kuhn f -sum rule. The estimates used in these calculations are listed in the fifth column. The total number of oxygen atoms per square centimeter of the reversing layer, as determined from each of the lines, is given in the ninth column. In calculating the figures in the ninth column from those in the eighth column, a Boltzman factor corresponding to an excitation temperature of 5200° was used. This value of the excitation temperature was obtained by varying the temperature until the total number of oxygen atoms given by the high excitation-potential lines was approximately equal to that given by the low excitation-potential lines. Because of the very large difference in

the excitation potential of the two groups of lines, this provides an accurate method for the determination of the excitation temperature. Thus, a change of 100° in the assumed temperature shifts the relative abundances obtained from the two groups of lines by a factor of 1.5. This procedure, of course, means that the abundance of oxygen atoms depends almost entirely on the intensities of the low excitation-potential forbidden lines, while the intensities of the high excitation-potential permitted lines are used primarily for the determination of the excitation temperature.

The average value of the number of oxygen atoms per square centimeter of the reversing layer, 7×10^{20} , corresponds to 18 mg of oxygen per square centimeter. Since practically all the oxygen in the reversing layer is in the neutral state, this figure also represents the total amount of oxygen in all stages of ionization. This value is nearly twice the best previous estimate⁵ of 10 mg per square centimeter, but is well within the probable error of the earlier value.

The appearance of these O I forbidden lines raises the question of the use of forbidden lines for the determination of the abundances of other elements whose permitted lines in the observable range have too high excitation potentials to yield accurate values. Table II lists information on the four most abundant elements of this group. The second column of this table gives the best available estimate of the number of neutral atoms per square centimeter in the reversing layer. These values were obtained by combining

TABLE II. Equivalent widths of forbidden lines of abundant atoms.

Atom	Neutral atoms per sq.cm.	λ	Transition	Transition probability A (sec. ⁻¹)	Excitation potential	Calculated equivalent width W
C I	3×10^{19}	8727.4	$^1D \rightarrow ^1S$	1.4	1.26	0.002A
		9849.5	$^3P_2 \rightarrow ^1D$	0.00015	0.01	0.000,03
		9823.4	$^3P_1 \rightarrow ^1D$	0.00005	0.00	0.000,01
		4621.5	$^3P_1 \rightarrow ^1S$	0.0017	0.00	0.000,003
N I	10×10^{19}	5200.7	$^4S \rightarrow ^2D_{3/2}$	0.000021	0.00	0.000,003
		5198.5	$^4S \rightarrow ^2D_{1/2}$	0.000015	0.00	0.000,001
		3466.4	$^4S \rightarrow ^2P$	0.0094	0.00	0.000,15
		10991.52	$^1D \rightarrow ^1S$	3.3	0.78	0.023
Si I	2×10^{19}	6526.85	$^3P_1 \rightarrow ^1S$	0.036	0.01	0.000,2
		7724.7	$^1D \rightarrow ^1S$	3.0*	1.14	0.002
S I	2×10^{19}	4589.0	$^3P_1 \rightarrow ^1S$	0.1*	0.05	0.000,1

* Extrapolated.

⁵ D. H. Menzel and collaborators, reported in Goldberg and Aller, *Atoms, Stars and Nebulae* (The Blakiston Company, Philadelphia, 1943), p. 114.

⁴ S. Pasternack, *Ap. J.* 92, 129 (1940).

the total number of the atoms in all stages of ionization given by Menzel⁵ with the distribution between stages given by Russell.⁶ As in Table I, the transition probabilities, A , are taken from Pasternack⁴ or are extrapolated from his values. The equivalent widths in the seventh column were calculated with the aid of formula (1). Since the measurement of equivalent widths smaller than 0.001Å seems to be impractical with present techniques, it is evident that investigations are limited to three lines. The wave-lengths of two of these lines, $\lambda 7724.7$ and $\lambda 8727.4$, are

⁶ H. N. Russell, Mt. W. Contribution No. 383; Ap. J. 70, 11 (1929).

not known at the present time with sufficient accuracy to make positive identifications in the solar spectrum possible. The third line, at $\lambda 10991.52$, falls so close to an atmospheric line at $\lambda 10991.40$ that equivalent-width measurements will at best be very uncertain.

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The Ratio of Valence Electrons to Atoms in Metals and Intermetallic Compounds*

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It is shown that the numbers of valence electrons assigned to the γ -alloys, β -manganese and alloys with similar structure, and α -manganese by a new system of metallic valences agree closely with the electron numbers calculated for complete filling of important Brillouin polyhedra for these structures.

I. INTRODUCTION

WHEREAS chemical valence theory has provided a satisfactory systematization of the formulas of most organic and inorganic compounds, the intermetallic compounds have continued to present a puzzling problem. Some intermetallic compounds, such as Mg_2Sn , have formulas that can be correlated with the customary valences of the elements involved. Many others, however, seem to show in their formulas no correlation with chemical valence: examples are NaCd_2 , KHg_{13} , Cu_5Zn_8 , $\text{Cu}_{31}\text{Sn}_8$, Cu_9Al_4 , $\text{Fe}_5\text{Zn}_{21}$. Added interest is given to the problem by the fact that the last four of these compounds, with formulas that seem to show little relation to one another, are sufficiently similar in their properties, and different from other intermetallic

compounds, to indicate that they are to be classified together.

Only in recent years has progress been made in attacking the problem presented by these intermetallic compounds; at the present time we may say that, although there are a number of puzzling questions that remain unanswered, the beginning of a theory of the stability and other properties of the substances has been formulated.

Let us first consider, as an example, the copper-zinc system of alloys.^{1,**} The ordinary yellow brass of commerce is restricted in composition to the first (copper-rich) phase of the system. This phase, which has the face-centered cubic structure characteristic of copper, is followed successively, as the zinc content is increased, by the β -phase (body-centered cubic),

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** References are listed in the bibliography at the end of the paper.